Natural Mass Generation for the Sterile Neutrino

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Abstract

We point out that there is a serious cosmological problem in the supersymmetric standard model if a sterile neutrino is responsible for the solar neutrino oscillation, and propose a possible solution to this problem. We show that our solution induces naturally a mass of order 10^{-4} eV for the sterile neutrino, which is deeply related to the mechanism of supersymmetry breaking.

Two flavor active–sterile neutrino oscillation seems to be disfavored by recent Superkamiokande data on both atmospheric and solar neutrino experiments [1]. However, a recent global analysis of the solar neutrino data [2] suggests that both the small angle MSW oscillation and the quasi–vacuum oscillation (corresponding to $\Delta m^2 \simeq 10^{-7} - 10^{-9}$ eV^2) are still consistent solutions. It has also been pointed out recently [3] that an energy–independent active–sterile neutrino oscillation is well consistent with the present solar neutrino experiments with the exception of the $^{37}C\ell$ results. Thus, the sterile neutrino is still interesting, since it may explain all neutrino oscillation data including LSND experiments [4]. In this short paper we propose a natural mechanism for generating a small mass for the sterile neutrino ν_s, which induces a ν_e-ν_s oscillation together with the conventional seesaw mechanism [5]. This new mechanism is deeply related to the dynamics of supersymmetry (SUSY) breaking.

Before describing the model let us discuss a cosmological difficulty due to the presence of the sterile neutrino in the SUSY standard model. Since the sterile neutrino is a gauge singlet and its Yukawa coupling constant is very small ($y_s \simeq 10^{-15}$)[1], the scalar partner of ν_s has a very flat potential. Thus, it is quite natural to consider that it has a large value of order the Planck scale ($M_G \simeq 2.4 \times 10^{18}$ GeV) at the end of inflation and its coherent oscillation dominates the early universe like moduli fields in string theory. The lifetime of the scalar sterile neutrino is estimated as $\tau \simeq 10^4$ sec with the above small Yukawa coupling constant y_s and a mass $m \simeq 1$ TeV. It is well known that such late decays of massive heavy particles destroy the success of the big-bang nucleosynthesis [6].[2]

A solution to the above problem is easily given by introducing the following superpoten-

[1]This small Yukawa coupling, $W = y_s LHS$, induces a small Dirac-type mass for the sterile neutrino of order 10^{-4} eV, which is required for the solar neutrino quasi–vacuum oscillation. y_s should be similar in magnitude for the small angle MSW solution as well.

[2]The lifetime should be shorter than 0.1 sec to avoid this problem [7].

tial:[3]

$$W = h\frac{Z}{M_G}L_iHS, \tag{1}$$

where $L_i(i=1-3)$, H and S are supermultiplets of three families of lepton doublets, a Higgs doublet and the sterile neutrino, and Z is a supermultiplet responsible for SUSY breaking. Then, we get an A–term,

$$\mathcal{L} = hm_{3/2}\tilde{L}_iH\tilde{S}, \tag{2}$$

where $\tilde{L}_i$ and $\tilde{S}$ are scalar components of the supermultiplets L_i and S, respectively and H is the Higgs boson. We have used that the gravitino mass $m_{3/2}$ is given by the vacuum-expectation value (vev) of the F-component of the supermultiplet Z, that is,

$$m_{3/2} = \frac{1}{\sqrt{3}M_G}\langle F_Z\rangle. \tag{3}$$

Then, the lifetime of the scalar sterile neutrino becomes $\tau \simeq 10^{-26}$ sec and the scalar sterile neutrino is cosmologically harmless.[4] Here, we have assumed $m_{3/2} \simeq 1$ TeV.[5]

We now discuss the SUSY breaking sector. We adopt the SUSY breaking model found in Ref. [10], which is based on an SU(2) gauge theory with four quark doublets, Q^i_α ($\alpha = 1, 2$

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[3]This superpotential is also discussed in Refs. [8], [9].

[4]We wish to remark that the operator of Eq. (1) can provide a possible solution to the moduli problem that is generic in string theory. If S is identified as one of the moduli fields and L_i is $\bar{H}$ in Eq. (1), the cosmological problem associated with the moduli will be solved, very much in analogy to the scalar neutrino.

[5]For the large angle ν_e-ν_s quasi–vacuum oscillation, it is possible to evade the cosmological limit by choosing $y_s \sim 3\times 10^{-13}$, so that the ν_e-ν_s mass term is of order 0.1 eV. If the direct ν_e-ν_e mass term arising from the seesaw mechanism is of order 10^{-7} eV, the required Δm^2 for solar neutrinos will be generated. Such a scenario is not realized by the mechanism suggested in this paper as long as all relevant Yukawa couplings are O(1).

and $i = 1-4$). We introduce six gauge-singlet supermultiplets $Z_a (a = 1-6)$ and assume the following superpotential:

$$W = \lambda^a_{ij}\epsilon_{\alpha\beta}Q^i_\alpha Q^j_\beta Z_a. \tag{4}$$

It is shown in Ref. [10] that the effective low-energy superpotential is given by

$$W_{eff} = \lambda\Lambda^2 Z. \tag{5}$$

Here, Z is a linear combination of Z_a supermultiplets and Λ denotes the dynamical scale of the SU(2) gauge interactions. The Kahler potential takes, on the other hand,

$$K = ZZ^* - \frac{k}{2\Lambda^2}(ZZ^*)^2 + ..., \tag{6}$$

where k is a real constant and the ellipsis denotes higher-order terms of ZZ^*. If the coupling constant k is positive, [6] we have a unique vacuum

$$\langle Z\rangle = 0, \qquad \langle F_Z\rangle = \lambda\Lambda^2. \tag{7}$$

Thus, SUSY is dynamically broken and the sterile neutrino remains massless[7].

A crucial point observed in Ref. [11] is that the supergravity effects induce a small shift of the vacuum and the A-component of the Z has a small nonvanishing vev:

$$\langle Z\rangle \simeq \frac{\Lambda^2}{\sqrt{3}kM_G} \simeq \frac{m_{3/2}}{\lambda k}. \tag{8}$$

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[6]This is an important dynamical assumption in this paper. If the k is negative, the A-component of the Z has a vev of order the dynamical scale Λ, which induces too large a Dirac-type mass for the sterile neutrino ($m_{\nu D} \sim 1$ keV).

[7]We assume the standard Yukawa coupling, $W = fLHS$ to exactly vanish and consider the case where S has only grvitationally suppressed nonrenormalizable interactions. This will be the case if S is one of the moduli fields of string theory. For neutrino mixing with modulino fields, see e.g. Ref. [12]

Substituting this result, Eq. (8), into Eq. (1) we obtain a Dirac-type ν_i-ν_s mass ($i = e, \mu, \tau$) as

$$\mathcal{L} \simeq \frac{h}{\lambda k} \frac{m_{3/2}}{M_G} \langle H \rangle \nu_i \nu_s + hc. \tag{9}$$

The Dirac-type mass is of order 10^{-4} eV for $\frac{\lambda k}{h} \sim 1$.[8] It is now clear that if the Majorana mass for the active electron neutrino induced by the seesaw mechanism is of order 10^{-4} eV, the present model will naturally reproduce the solar ν_e-ν_s oscillation. Since the mechanism suggested here generates a ν_s-ν_i ($i = e, \mu, \tau$) mass term, and no direct ν_s-ν_s mass term, it turns out that the lighter eigenstate is predominantly in ν_s, and not in ν_e. The MSW resonance condition will not be satisfied for solar neutrinos in this case. Our scenario will prefer the quasi–vacuum oscillation solution [2] with the inclusion of the Chlorine experiment, or the energy–independent solutions advocated in Ref. [3] excluding the Chlorine experiment. In either case, the other two active neutrinos together with the electron neutrino may explain the atmospheric and LSND neutrino oscillations. While ν_e-ν_s MSW resonance does not occur for supernova neutrinos, $\bar{\nu}_e$-$\bar{\nu}_s$ resonance will occur within the supernova [14]. However, vacuum oscillations on its way from supernova to the Earth will regenerate $\bar{\nu}_e$, but with its flux reduced by half.[9] Such a reduction is not inconsistent with $\bar{\nu}_e$ data from SN1987A, but may be testable with future supernova neutrinos. It is interesting to note that the neutrino data from supernova alone makes the large ν_e-ν_s mixing preferable in our scenario, independent of solar neutrino data.

If one supposes a superpotential term $W = (SSZZ/M_G)$, in addition to Eq. (1), a direct Majorana mass term for the ν_s of order $m_{3/2}^2/M_G \sim 10^{-3}$ eV will result. In this case the small angle ν_e-ν_s MSW oscillation may become relevant for solar neutrinos. However,

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[8]If one identifies the sterile neutrino with a right-handed neutrino and keeps exact lepton-number conservation, one may have a light Dirac neutrino as discussed in Ref. [13].

[9]If $\bar{\nu}_s$ mixes also with $\bar{\nu}_{\mu,\tau}$, the supernova $\bar{\nu}_{\mu,\tau}$ are also converted into $\bar{\nu}_s$ through the MSW resonances. In this case the $\bar{\nu}_e$ flux is enhanced by factor 3/2 instead.

this operator is less motivated (compared to the one in Eq. (1)) from the point of view of cosmology.

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